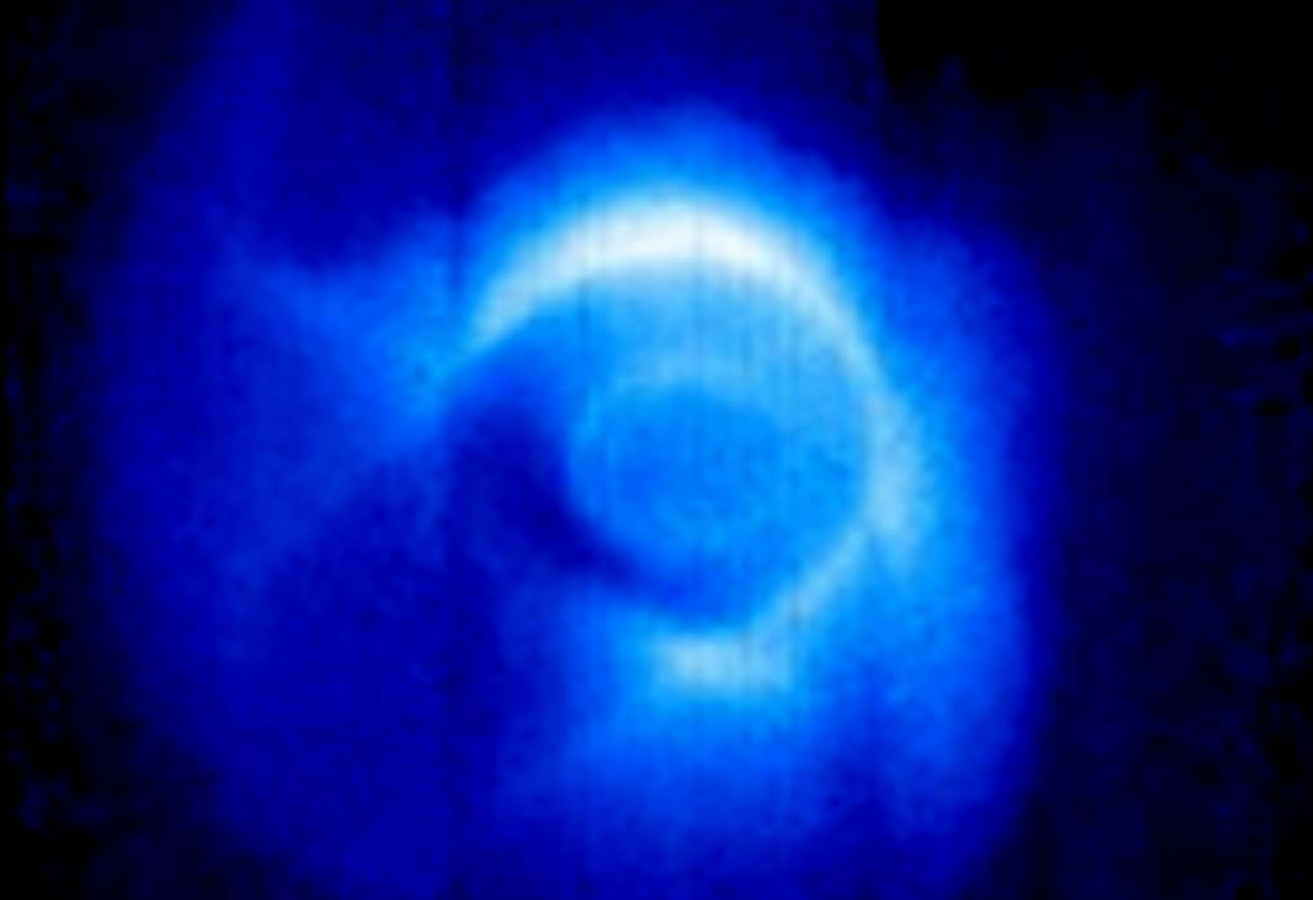
Inner Magnetospheric Physics



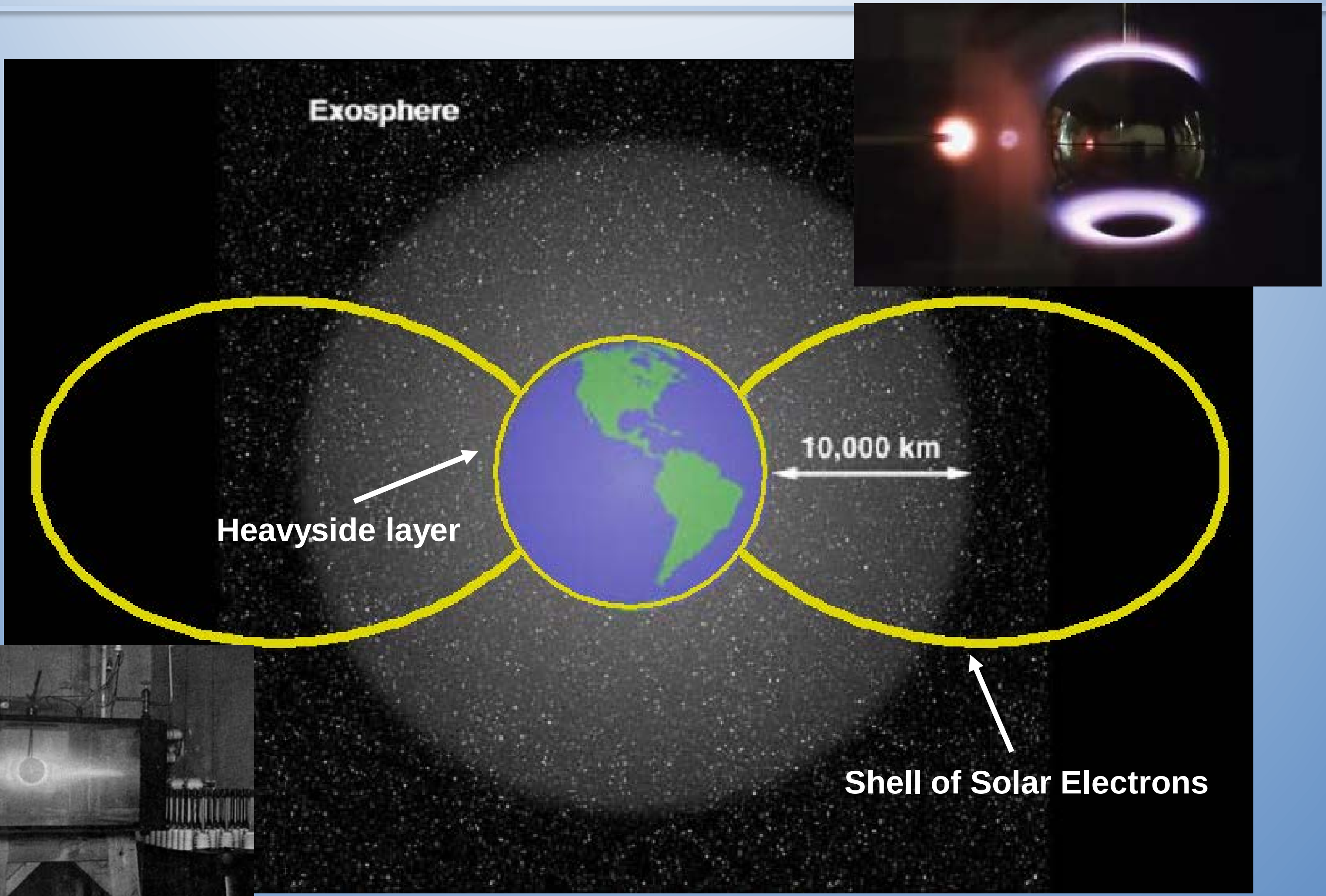
Dennis Gallagher, PhD
NASA Marshall Space Flight Center
dennis.gallagher@nasa.gov

Inner Magnetosphere Effects

- Historical Background
- Main regions and transport processes
  - Ionosphere
  - Plasmasphere
  - Plasma sheet
  - Ring current
  - Radiation belt
- Geomagnetic Activity
  - Storms
  - Substorm
- Models

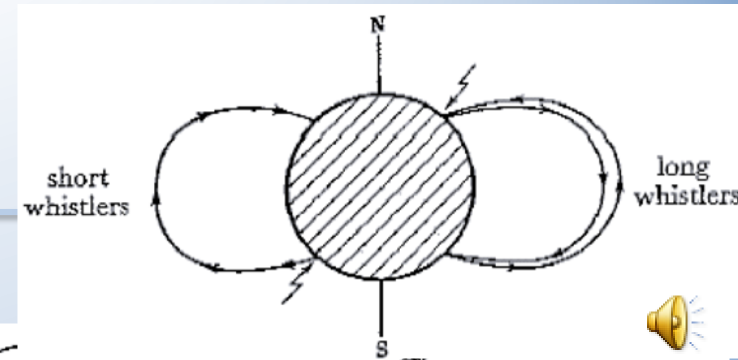
Outline

Historical Background: Space in 1950



Historical Background

Whistlers revealed unexpected plasma



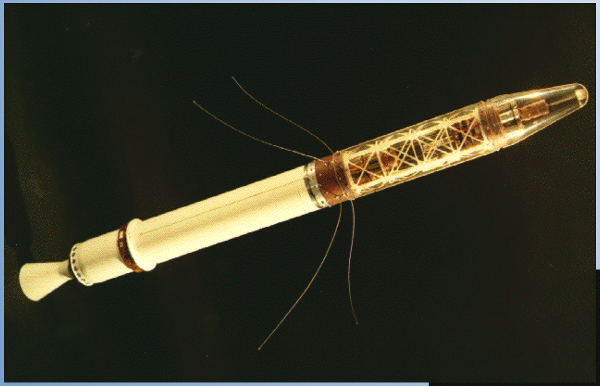
Whistlers

1952
L. R. Owen Storey
Cavendish Laboratory
University of Cambridge

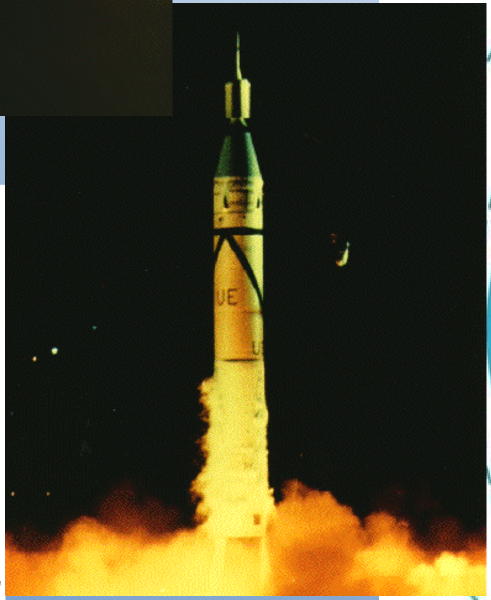
L. R. O. Storey, Phil. Trans. R. Soc. Lond. A 1953 246 113-141; DOI: 10.1098/rsta.1953.0011. Published 9 July 1953

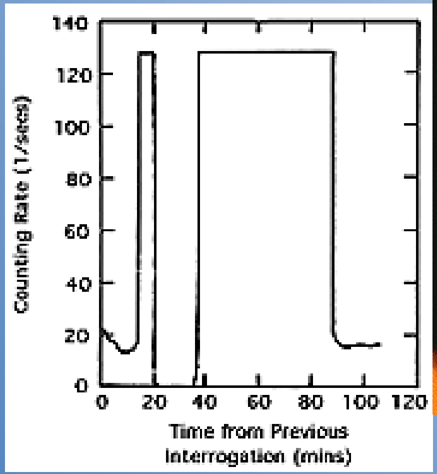
Historical Background

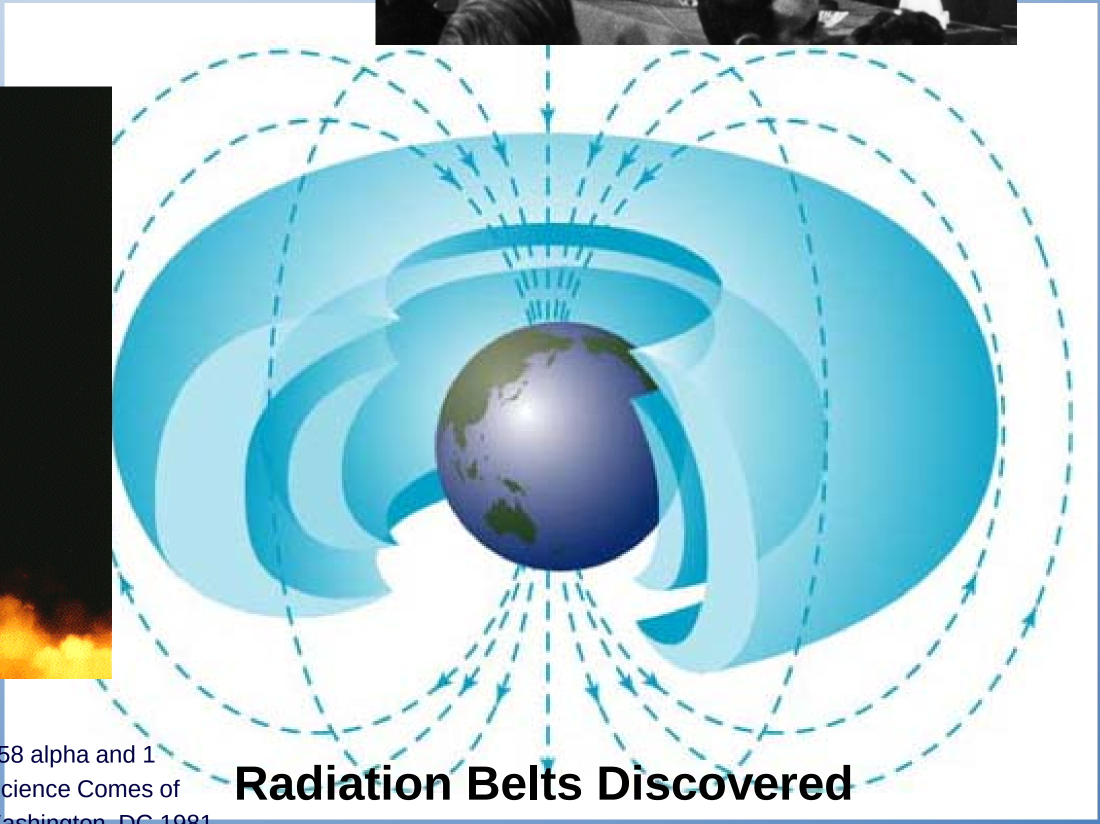
Explorer 1
January 31, 1958



Pick







Radiation Belts Discovered

Van Allen, James A., Observation of high intensity radiation by satellites 1958 alpha and 1958 gamma, IOWA Univ. preprint SUI 60-13, reprinted in p. 58-75, Space Science Comes of Age, P.A. Hanle and V.D. Chamberlain, editors, Smithsonian Inst. Press, Washington, DC 1981

Ionosphere

Reactions

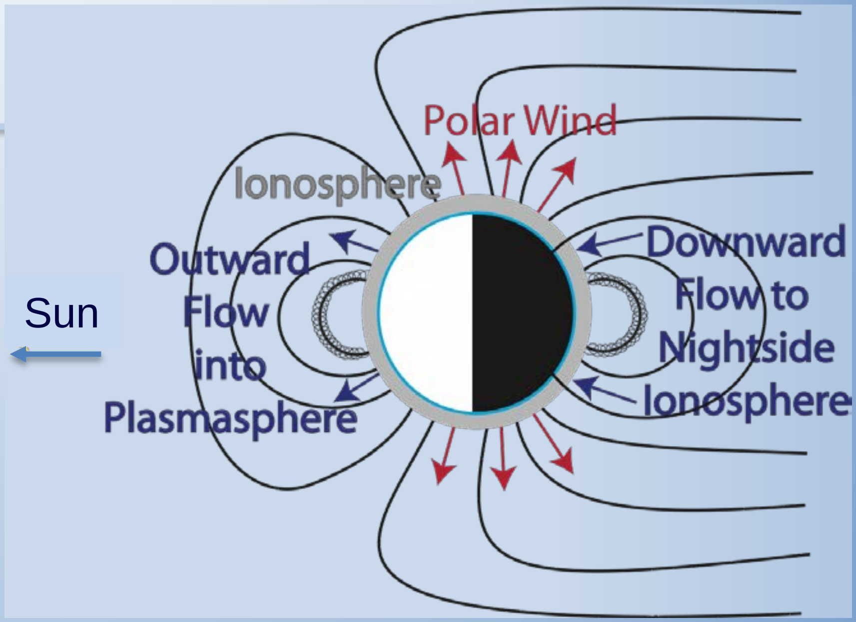
$X+\gamma \rightarrow X^{+}+e^{-}$	$XY+\gamma \rightarrow X+Y$	$X^{+}+e^{-} \rightarrow X$
$X^{-}+Y \rightarrow XY+e^{-}$	$X^{+}+YZ \rightarrow YX^{+}+Z$	$X^{+}+e^{-} \rightarrow X+\gamma$
		$XY+e^{-} \rightarrow Y+X$
		$X+e^{-} \rightarrow X^{-}$

Common Constituents

X-rays, EUV, O, N, O_2, N_2, NO, H, O_3

- Ionosphere: ionized portion of upper atmosphere
  - Extends from around 60 km to beyond 1000 km
  - Completely encircles the Earth
  - Main Source: photoionization of neutrals
    - Other production processes dominate in different ionospheric regions
  - Loss Mechanism: ionospheric outflow, recombination

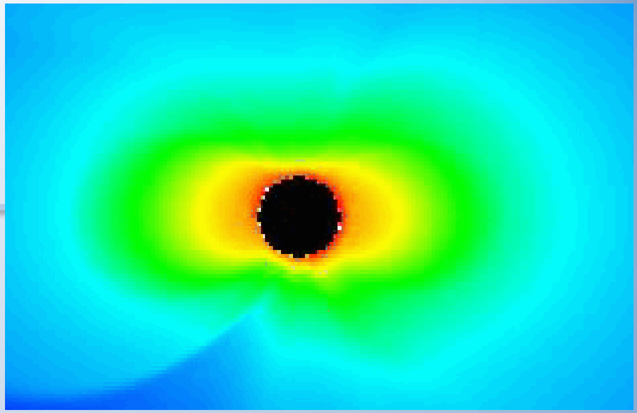
Ionosphere outflow



- Main cause
  - Ambipolar electric field
  - pressure gradients
  - Mirror force due to gyration of charged particles
- Polar wind: Ionospheric loss at polar latitude
  - Along essentially open geomagnetic field lines
- At mid-latitudes the plasma may bounce to the conjugate ionosphere or become the plasmasphere

Main regions and transport processes

Plasmasphere Formation: Diffusive Equilibrium



$$H_j = \left(\frac{kT_i}{m_j g}\right)\left(1 - \frac{m_a T_e}{m_j T_t}\right)^{-1}$$

H_j = scale height

k = Boltzmann constant

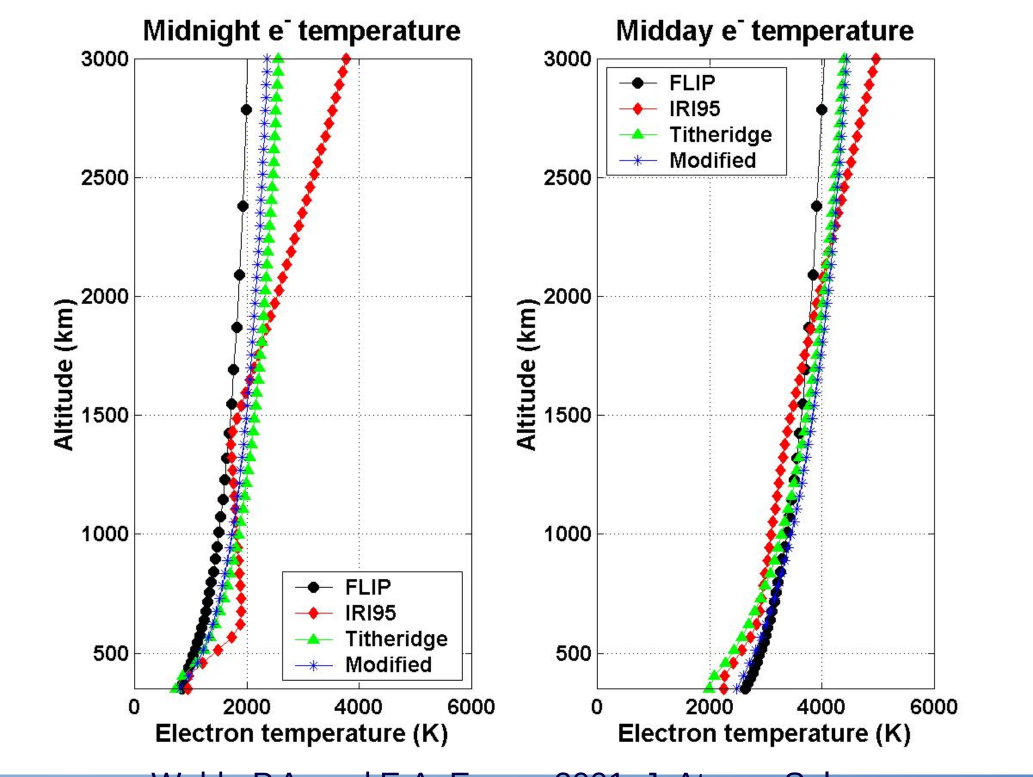
m_j = j'th ion mass

g = gravitational constant

m_a = mean ion mass

T_e = electron temperature

$T_t = T_i + T_e$ total temperature



Titheridge, J.E., Planetary and Space Science, 20 (1972), pp. 353-369

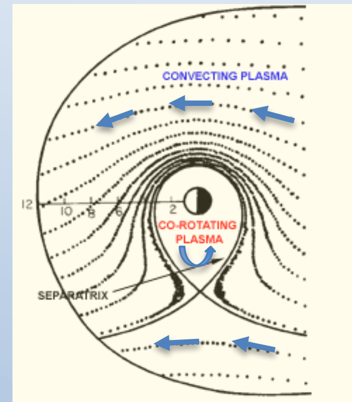
Webb, P.A. and E.A. Essex, 2001, J. Atmos. Solar Terres. Phys., 63, 11, pgs 1249-1260, doi:10.1016/S1364-6826(00)00226-1

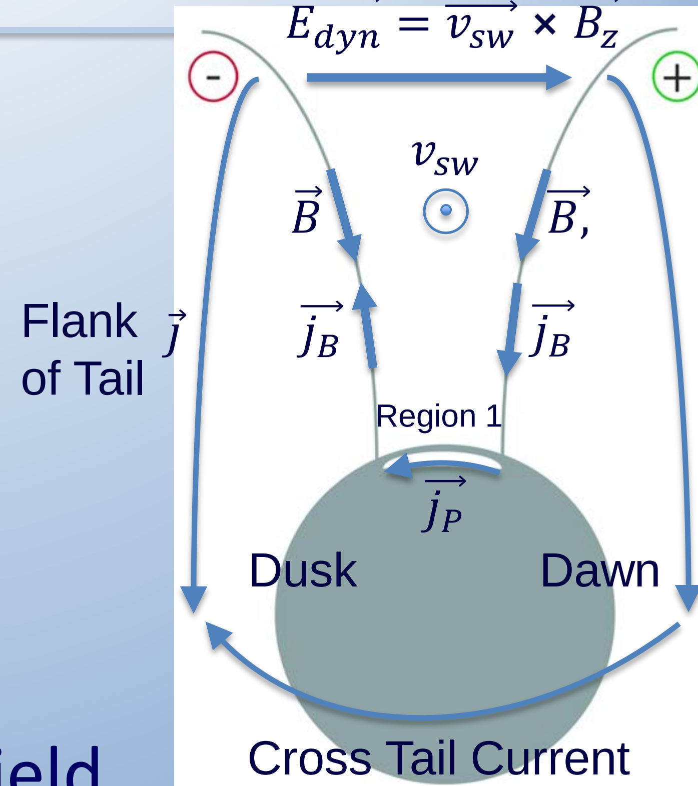
Solar wind dynamo

$$\overrightarrow{F_{Lorentz}} = q\vec{E}$$

$$\overrightarrow{E_{dyn}} = \overrightarrow{v_{sw}} \times \overrightarrow{B_z}$$

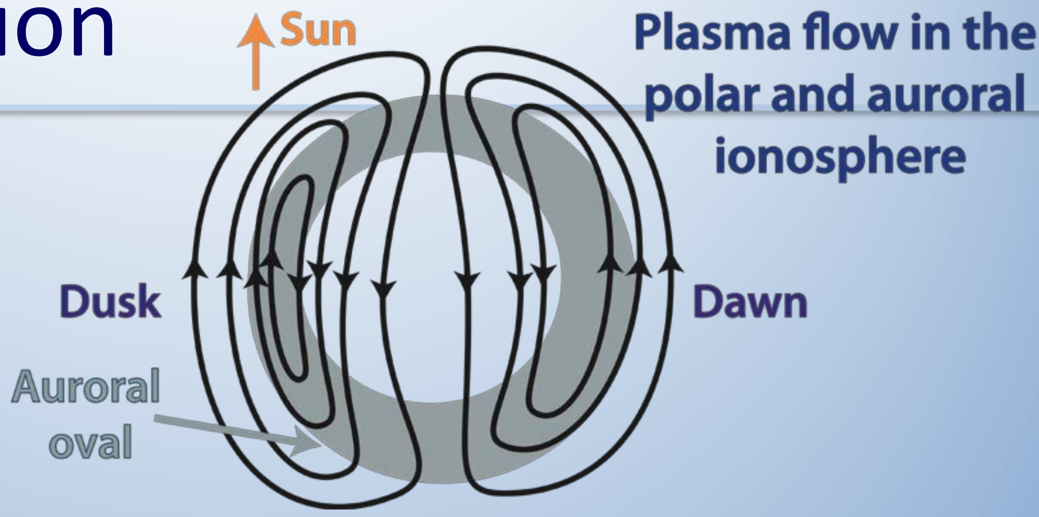
- Highly conducting plasma in the solar wind flows across polar geomagnetic field lines
  - Induces an electric dynamo field
  - Plasma and B-field lines are transported: Frozen-in flux concept





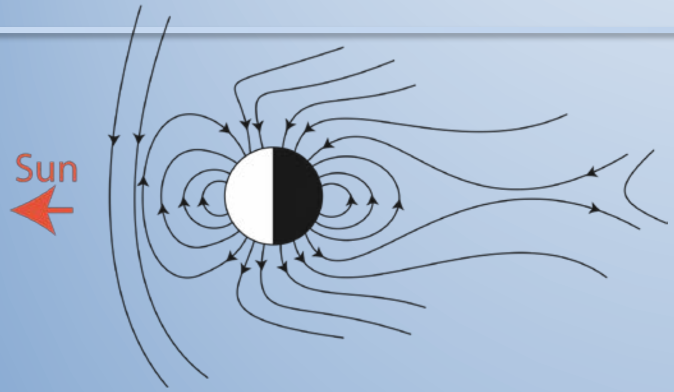
Main regions and transport processes

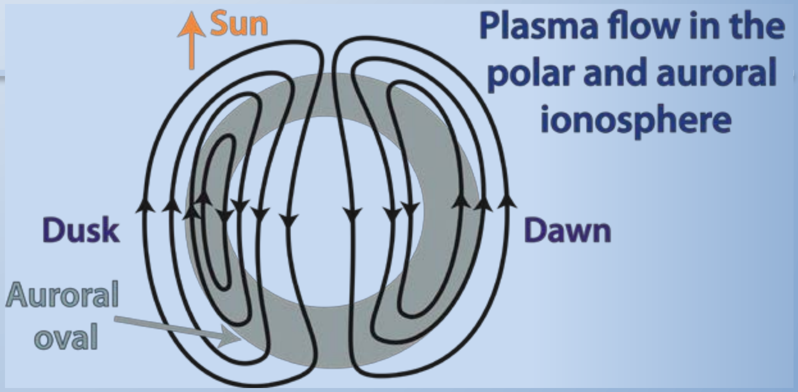
Global convection



- In the Late 50s, ground-based measurements revealed the plasma flow pattern in the polar and auroral ionosphere
  - Anti-sunward flow over the polar cap and
  - Return flow equatorward of the auroral oval
- In 1959 Gold introduced the term convection
  - Resemblance to thermally driven flow cells

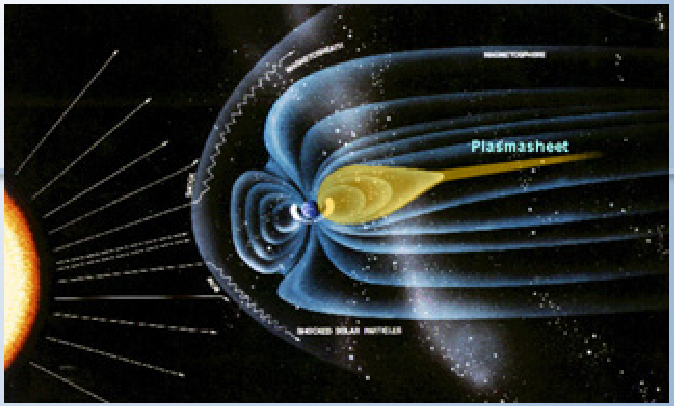
Reconnection





- If the polar geomagnetic field lines are open
  - The electric field produces an anti-sunward ExB drift of solar wind and magnetospheric plasma across the polar cap
  - Reconnection occurs down tail
  - Closed geomagnetic field lines flow back towards Earth at lower latitudes

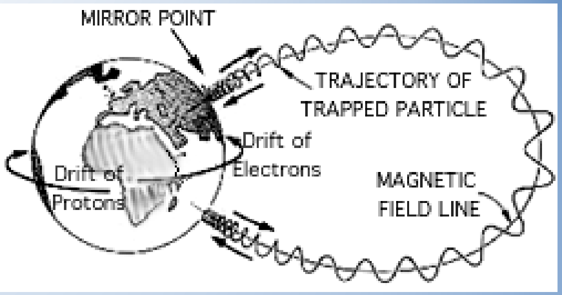
Plasma sheet



- Plasma sheet: population of ionospheric and solar wind particles being accelerated Earthward
- Neutral current sheet: large-scale current flow from dawn to dusk across the plasma sheet
  - Separates the two regions of oppositely directed magnetic field in the magnetotail
  - Accelerates particles towards Earth
- Direct access to night side auroral oval
  - Can fall into the atmosphere producing aurora

AKR

Adiabatic Invariants



Electrons and ions in a plasma follow paths driven by the changing ambient magnetic and electric fields. Three basic motions are described by the Adiabatic Invariants (μ,*J*,Φ).

Gyration of a charged particle in a magnetic field results in it having a magnetic moment, the first Invariant:

$$\mu = \frac{mv_{\perp}^2}{2B}$$

A gyrating particle will bounce between regions of stronger magnetic field, the second Invariant:

$$J = \int_a^b v_{\parallel} ds$$

A bouncing particle on a planet's magnetic field drifts azimuthally, leading to the third Invariant:

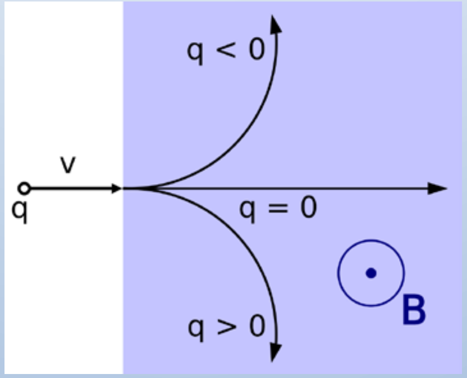
Φ = the total magnetic flux enclosed by a drift surface

First Adiabatic Invariant

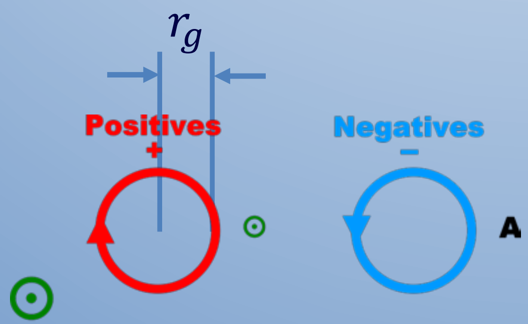
$$F = q\vec{E} = q\vec{v}x\vec{B}$$

$$\mu = \frac{mv_\perp^2}{2B}$$

$$\boldsymbol{\varepsilon} = \frac{1}{2}mv_\parallel^2 + \frac{1}{2}mv_\perp^2$$



$$r_g = \frac{mv_\perp}{2B}$$



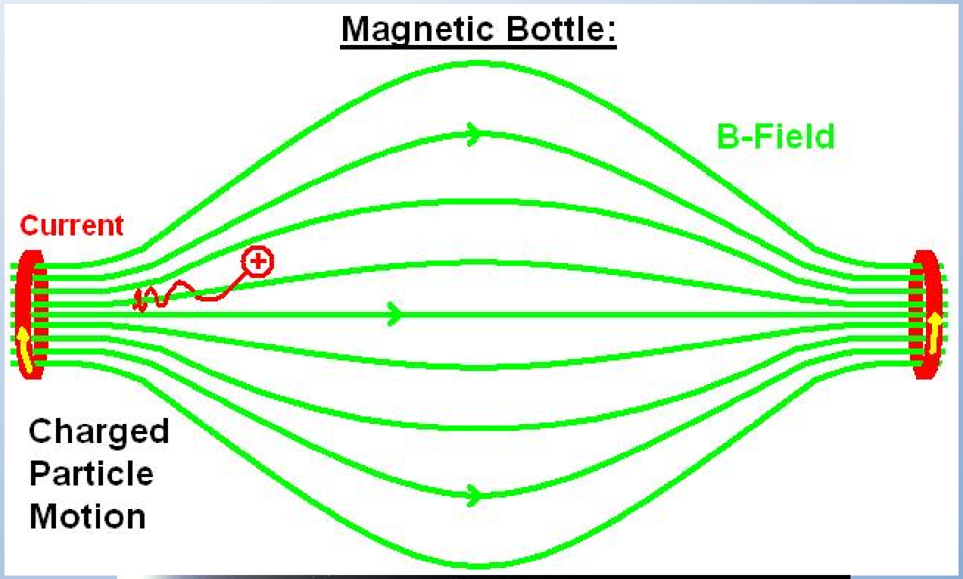
For H^+, T=1eV, L=4

f_g = 114 Hz

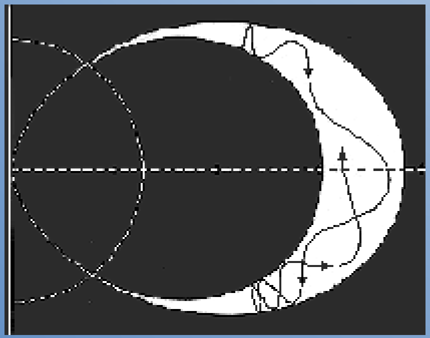
r_g = 13.6 m

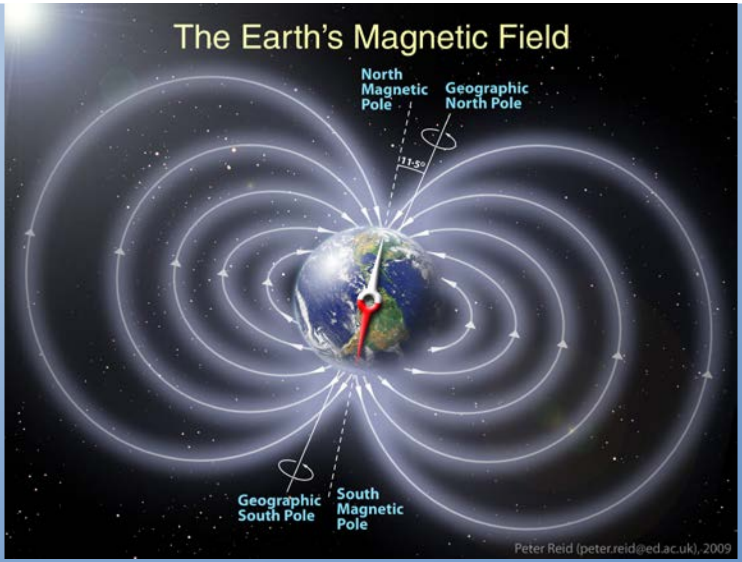
Second Adiabatic Invariant

$$J = m \oint v_{\|} ds$$



Bounce Period ~1 s

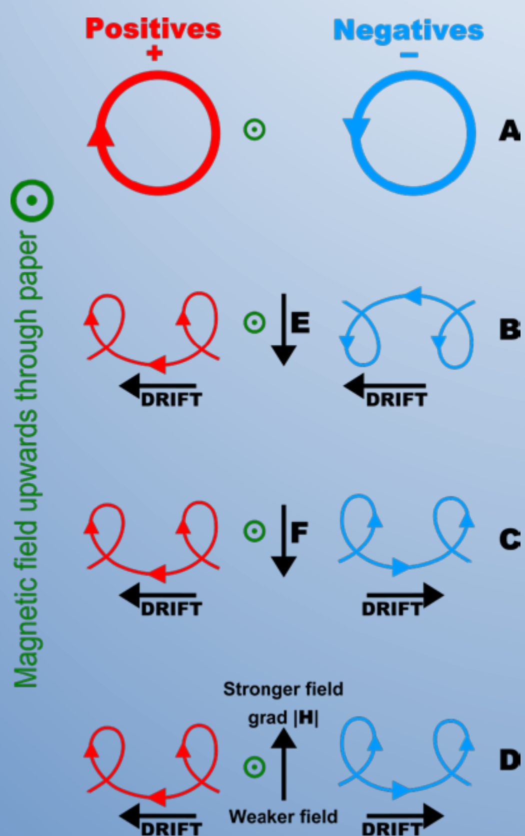




Main regions and transport processes

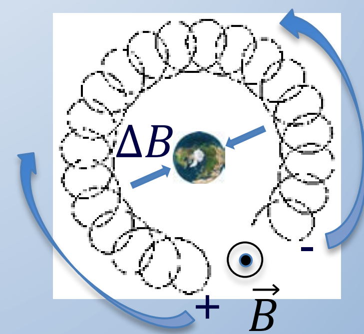
Third Adiabatic Invariant

$\Phi = \pi R^2 B$ Flux conservation inside the drift surface



Gradient-B Drift

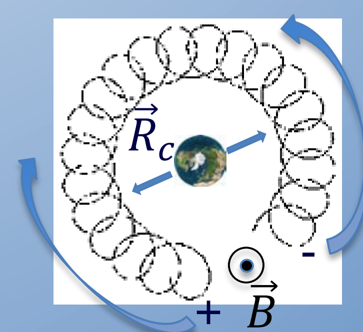
$$\vec{v}_{\nabla B} = \frac{\varepsilon_\perp}{qB} \frac{\vec{B} \times \Delta B}{B^2}$$



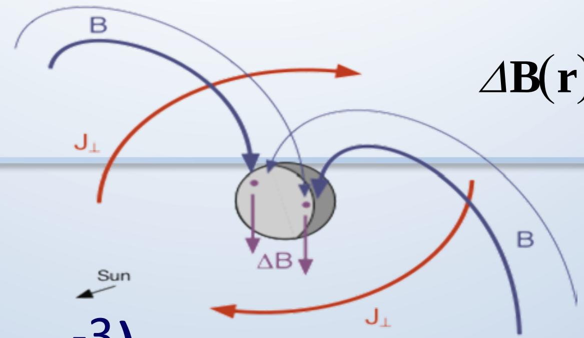
10s seconds

Curvature-B Drift

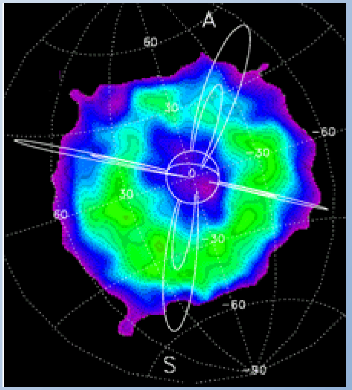
$$\vec{v}_R = \frac{\varepsilon_\parallel}{qB} \frac{\vec{R}_c \times \vec{B}}{R_c^2 B^2}$$



Ring Current



$$\Delta\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\int_V \frac{\mathbf{J}(\mathbf{r}')\times(\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3}\,d\mathbf{r}'$$

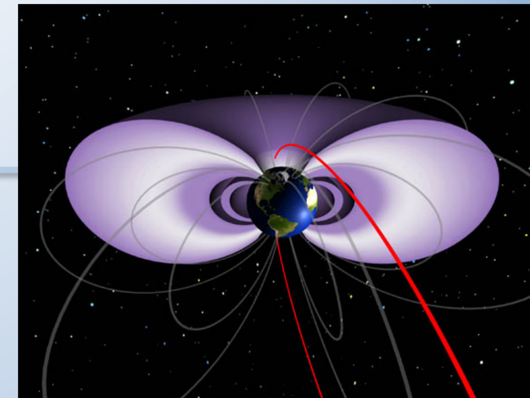


- Hot (1-400 keV) tenuous (1-10s cm^{-3})
- diamagnetic current produced by motion of plasma trapped in the inhomogeneous geomagnetic field
  - Torus-shaped volume extending from ~3 to 8 R_E
  - Main Source: plasma sheet particles
  - Loss Mechanisms: charge exchange, coulomb collisions, atmospheric loss, pitch angle (PA) diffusion, and escape from magnetopause

Chorus

Main regions and transport processes

Radiation Belt

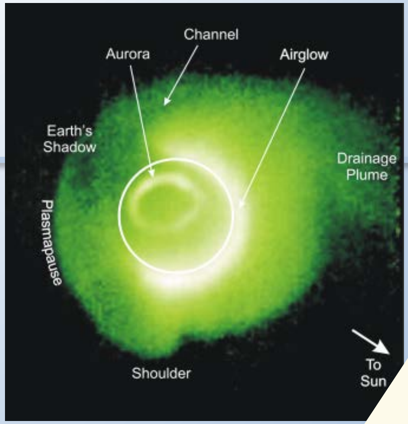


- Very Hot (100s keV - MeV)
- Extremely tenuous: <<1 cm^{-3}
  - Outer belt: very dynamic region
    - Mostly elections located at 3-6 R_E
  - Inner belt: fairly stable population
    - Protons, electrons and ions at 1.5-2 R_E
- Source: injection and energization events following geomagnetic storms
- Loss Mechanisms: Coulomb collisions, magnetopause shadowing, and PA diffusion

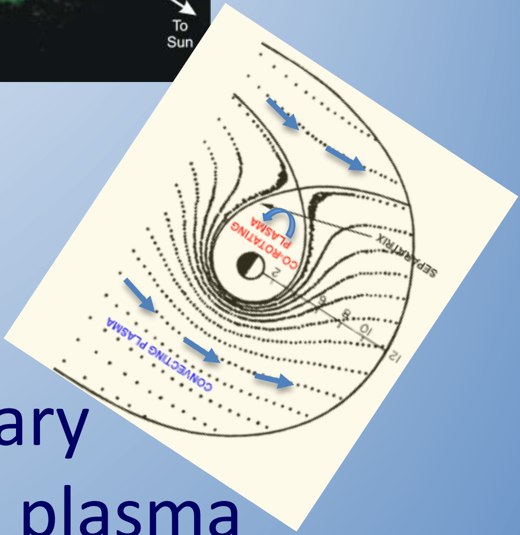
Hiss

Main regions and transport processes

Plasmasphere



- Cool (<10 eV)
- High density (100s-1000s cm^{-3})
- Co-rotating plasma
  - Torus-shaped, extends to 4-8 R_E
  - Plasmapause: essentially the boundary between co-rotating and convecting plasma
- Main Source: the ionosphere
- Loss Mechanism: plasmaspheric erosion and drainage plume



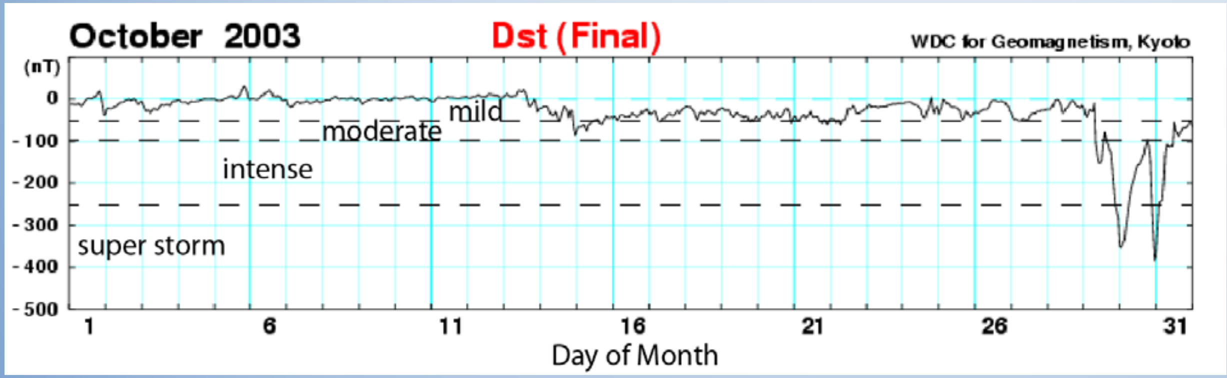
Main regions and transport processes

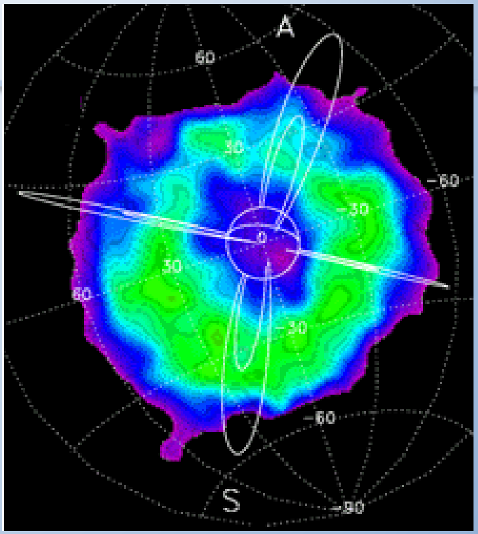
Geomagnetic storms

- Large (≥100s nT – reduced B-field on Earth's surface due to ring current)
- Prolonged (days)
- Magnetospheric disturbances
  - Caused by variations in the solar wind
  - Related to extended periods of large southward interplanetary magnetic field (-IMF Bz)
    - Increasing the rate of magnetic reconnection
    - Enhancing global convection

Geomagnetic storms

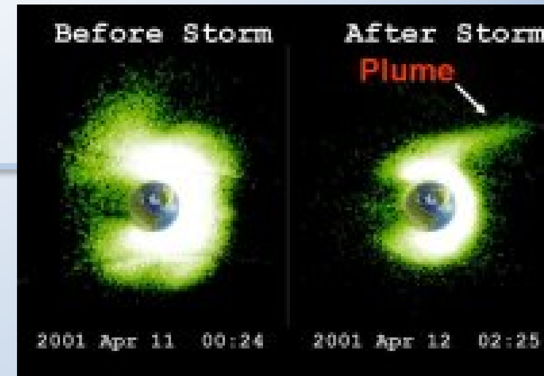
Halloween Storm of 2013



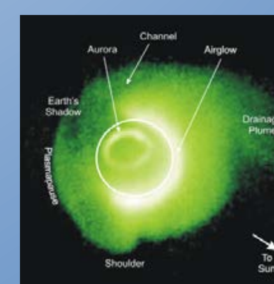


- Enhanced convection
  - Increased rate of injection into the ring current
    - The ring current then expands earthward
    - Induced current can reduce the horizontal component of the geomagnetic field (100s nT)
      - Used to calculate Dst

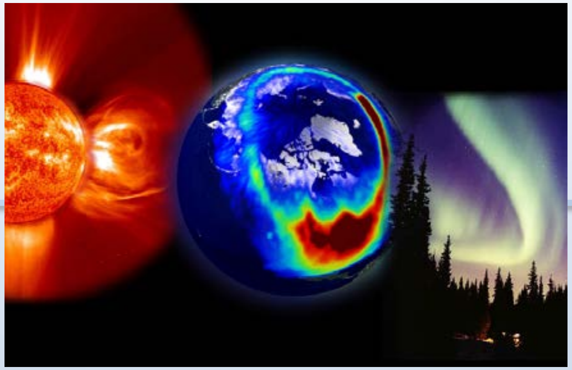
Plasmaspheric Plumes



- Enhanced convection also causes the co-rotating plasmaspheric material to surge sunward
  - Decreasing the night-side plasmapause radius
  - Extending the dayside plasmapause radius
- Creates a plume extending from ~12 to 18 MLT
- For continued enhanced convection less material remains to feed the plume and it narrows in MLT
  - Dusk edge remains almost stationary
  - Western edge moves eastward

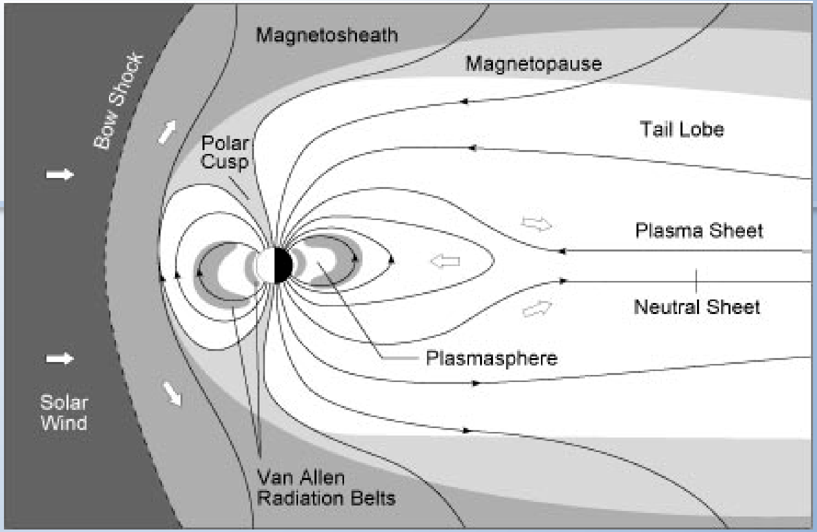


Substorms

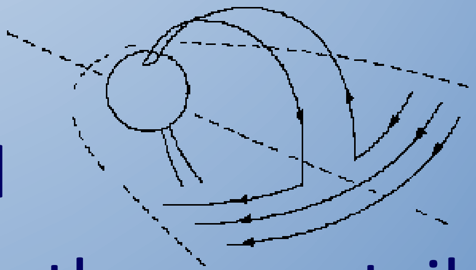


- A relatively short (hours) period of increased energy input and dissipation into the inner magnetosphere
  - Events may be isolated or occur during a storm
  - Associated with a flip from northward to southward IMF Bz
- Increased rate of reconnection
- Increased flow in magnetospheric boundary layer
- Release of energy accumulated in the near-Earth tail

Substorms



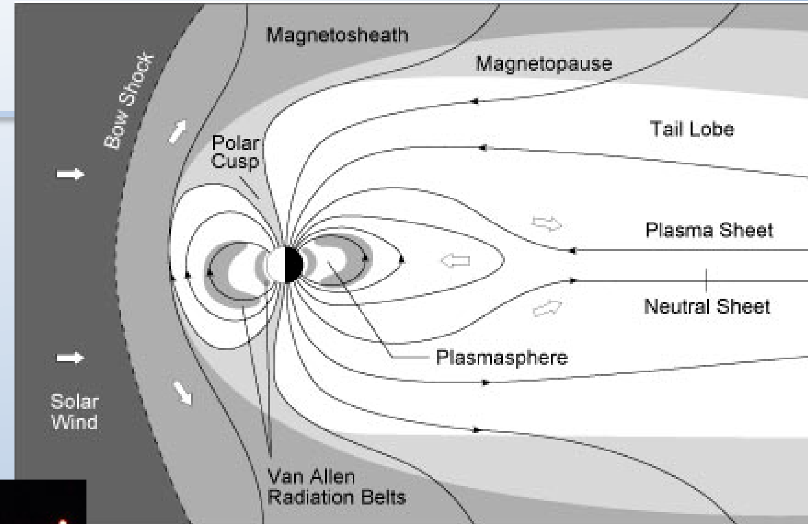
- Additional magnetic flux in the tail lobes causes the cross-tail current sheet thickness to decrease
  - When the current sheet thickness reaches its threshold reconnection occurs
  - The cross-tail current is disrupted

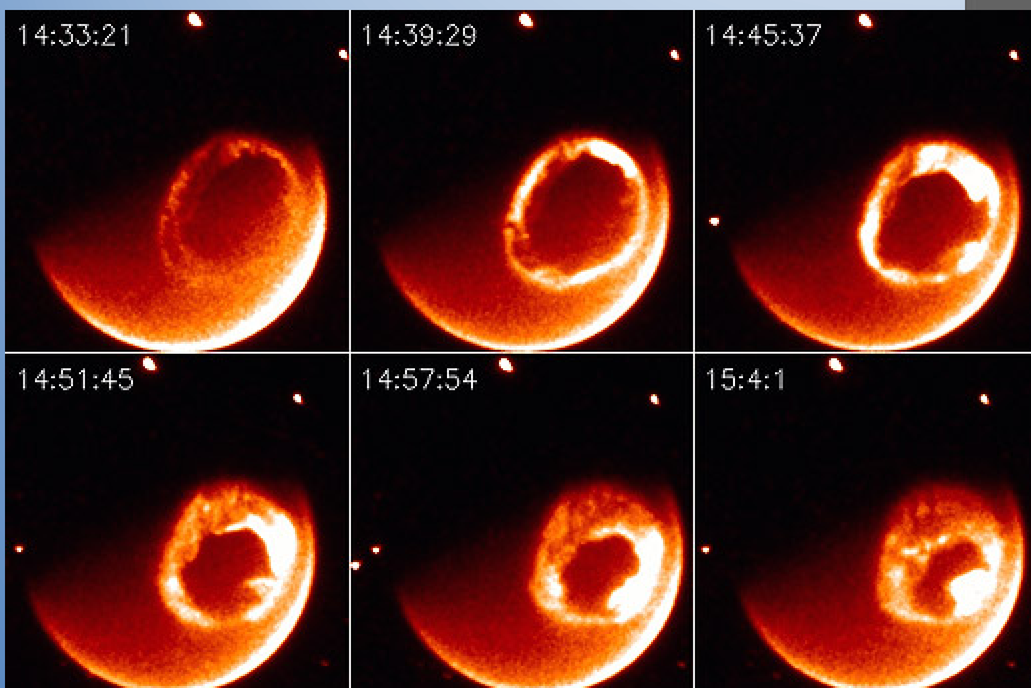


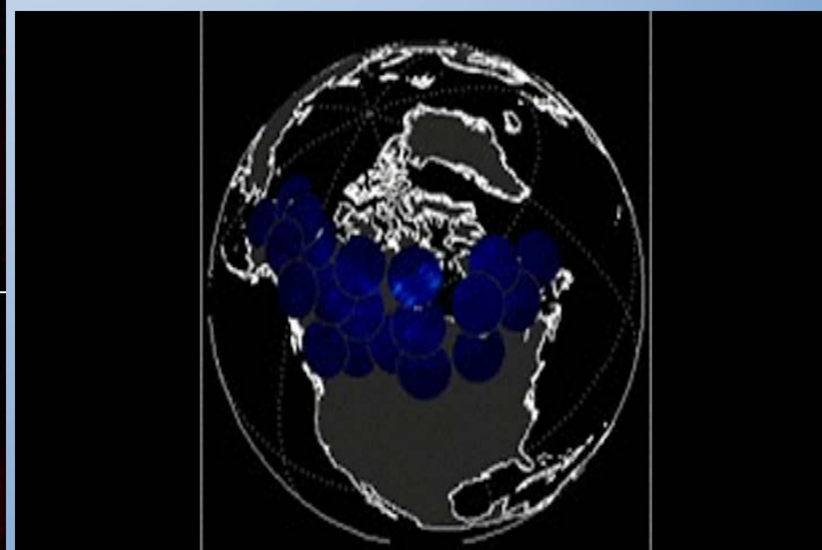
- The substorm current wedge closes the cross-tail current through the ionosphere
- Particle precipitation increases Auroral activity

Substorms

Reconnection in the magnetotail initiates a depolarization event. Inward transport causes plasma to be energized and lost into the atmosphere. Drift fills the ring current. Wave-particle interactions scatter plasma into the atmosphere. The auroral fills the auroral oval.





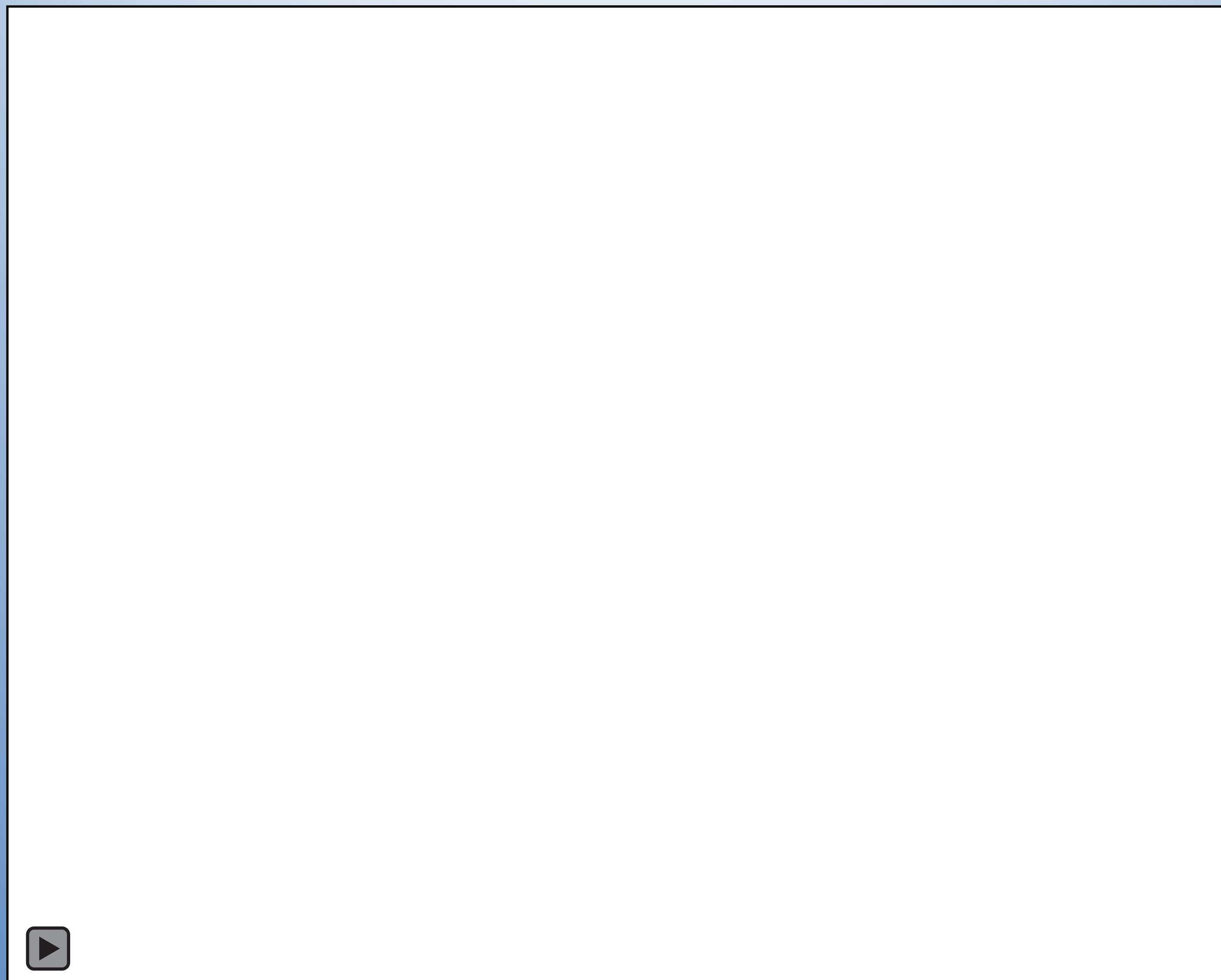


ESA/NASA Cluster Mission

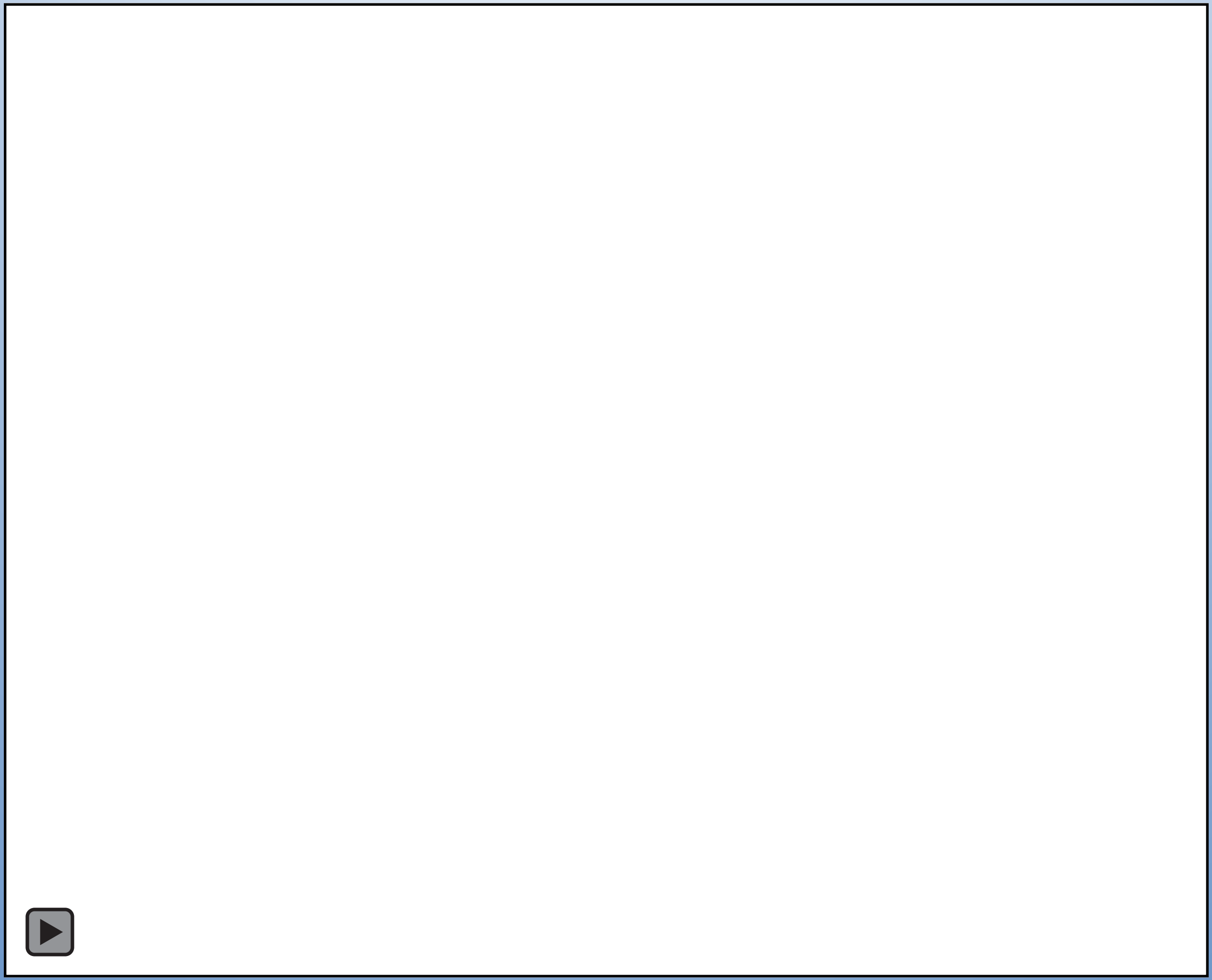
NASA IMAGE Mission

Geomagnetic Activity

Models – Empirical: IRI



Models – Empirical: GCPM

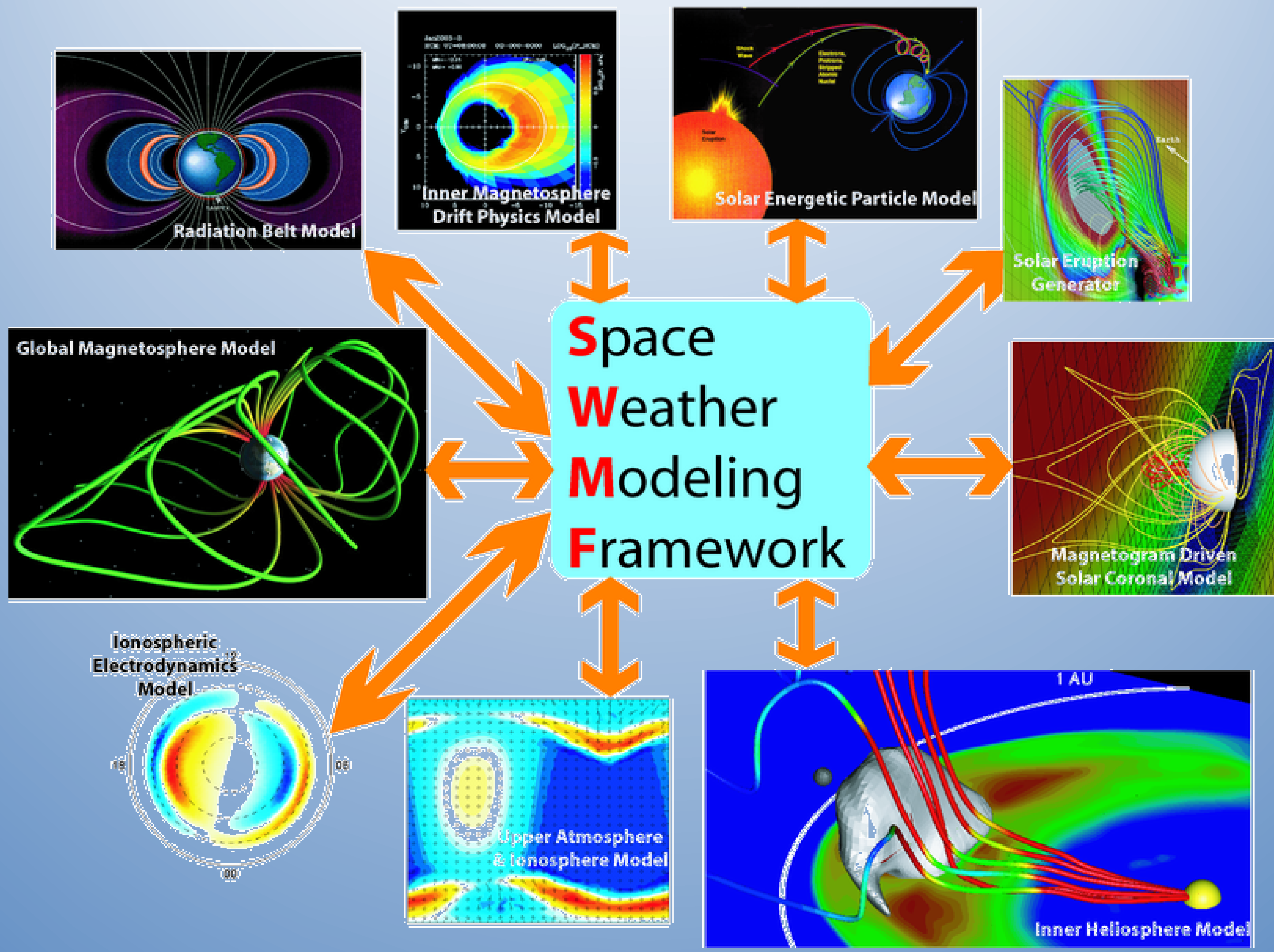


Models –LFM Model (Multi-Fluid Lyon-Fedder-Mobarry MHD)

Lyon, Fedder, Mobarry, DOI: 10.1016/j.jastp.2004.03.020

Through the Coordinated Community Modeling Center, NASA/GSFC

Coupling Models



Tóth, et al., The Space Weather Modeling Framework, *Proceedings of ISSS-7*, 26-31, March, 2005